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Mechanical properties (MOE and MOR) of glulam

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By

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Main Advisor Second Reader

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ABSTRACT

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Glue-laminated (glulam) timber has strong mechanical properties and is a great building material. It is composed of small diameter wood. There has been a shortage of large dimensional lumber for construction projects. Glulam is the solution for this since it can be manufactured to have impressive dimensions and unique arches.

Glulam from Nordic, a manufacturer in Quebec was tested for density, MOE and MOR values. Samples were cut from bolts and only the pieces that make up the glulam bolt were tested. The density was tested on 20 samples and a two-way ANOVA was completed to compare the orientation (parallel and perpendicular) of the glulines and to compare the samples with adhesive to the clear samples (joint type). There was a significant difference in the orientation, parallel wood was a higher density. Two-way ANOVAs were also run to compare the MOE and MOR values for each glulam bolt, orientation and joint type. There were 80 samples used and no significant differences found. This can be explained due to the nature of glulam. It was the pieces that make up the beam being tested and there were many inconsistent defects (ex. knot size and frequency) throughout the samples. Many defects are hidden within a glulam beam. As a whole product it is accepted that glulam is a strong, effective building material.

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INTRODUCTION

Creating engineered wood such as glulam has provided an opportunity to create structurally improved wooden posts and beams. Glulam beams can be created in various sizes and with various arcs (Gilfillan et al. 2003). Glulam is most commonly used in buildings because of the long dimensions it can be constructed to have or because of the unique curves, which can enhance architectural design (Ramage et al. 2016). The only limitations to the glulam dimensions are the manufacturing capabilities of the company or the method of transportation (Moody and Hernandez 1997). Companies are also able to gain added profit through using lesser-valued wood in the production of glulam (Gilfillan et al. 2003). The company Nordic, based out of Quebec uses small diameter black spruce to produce higher valued glulam beams.

Another benefit of using value-added wood products is to mitigate climate change. Since wood is a carbon sink it can be used as an environmentally conscientious building material. As climate change becomes more pertinent to social and political discussion, there is an increase to the popularity of using environmentally conscientious building materials (Ramage et al. 2017). Wooden structures can also be beneficial in areas prone to earthquakes (Ramage et al. 2016). Since the cellular structure of wood permits the material to flex, wooden structures have been proven to be more durable under earthquake conditions (Ramage et al. 2016).

In Ontario the building codes have been challenged to change and continue to be challenged. A major change was the permission in 2015 to build a wooden framed building up to 6 stories tall. The public perception of wooden buildings is changing and becoming more popular (Ramage et al. 2016). It can be proven that building even taller structures can be safe and effective. Engineered wood, especially glulam is an effective building material for this purpose.

The pieces that make up the beams will be tested for their modulus of elasticity (MOE) and modulus of rupture (MOR). The MOE test examines the stiffness of the glulam and is also referred to as Young's test. The MOR test examines the bending strength of the glulam beam to failure, it is a strength and stiffness correlation. Both of these tests can be used to determine the effectiveness of building wooden structures with the glulam beams and what the limitations may be (Verkasalo and Leban 2003).

RESEARCH OBJECTIVE

1. To determine the MOE and MOR of black spruce glulam pieces.
2. Contribute to the topic of using engineered wood, especially glulam, to build taller wooden structures.

RESEARCH QUESTION

Is there a significant difference between:

- Glulam bolts?
- Orientation of glue lines (parallel or perpendicular)?
- Joint type (Clear samples or with samples with adhesive)?

LITERATURE REVIEW

WHAT IS GLULAM?

Glulam is a value-added wood product composed of smaller pieces of lumber that are glued together with a specialized adhesive (Williston 1991). The beam pieces are oriented to be parallel to the longitudinal axis (Moody and Hernandez 1997). The specific type of adhesive used is important to make a quality glulam product (Williston 1991). There are many different types of adhesives and all can be optimal in different situations (Williston 1991). Two of the main adhesives are urea-formaldehyde (UF) resins and phenol-formaldehyde (PF) resins (Pizzi and Mittal 2003). UF resins are the most commonly used adhesives for wood products (Pizzi 1994). A few features of UF resins are that they have no colour, are nonflammable and have high hardness. PF resins were the first synthetic resins to be produced commercially. A few features of the PF resins are that they can be produced at a relatively low cost, are water resistant, have high-temperature resistant and are weather resistant (Pizza 1994). The features of PF resins allow it to be an external grade adhesive (Pizza and Mittal 2003). Additionally, tannin-formaldehyde wood adhesives are used in glulam manufacturing and have been since the early 1970’s (Pizza 1994). All glulam wood pieces must be kiln dried prior to being combined (Moody and Hernandez 1997). The standard moisture content is 12% and there can be no more than a 5% variance in moisture content (Moody and Hernandez 1997). A drastic variance in moisture after the adhesive has been applied can compromise the structural integrity of the product (Moody and Hernandez 1997). The wood is most likely to form checks, splits, warp or any other defect during the drying process (Moody and Hernandez 1997). Growth defects or drying defects from low-value or low-grade lumber pieces can be removed and structural properties improved once they are combined with an adhesive (Williston 1991).

The wood pieces can be combined through different joining techniques (Williston 1991). The process can be difficult to achieve a consistent joint strength throughout the product (Moody and Hernandez 1997). With careful cutting, the application of adhesives and appropriate clamping force, a quality product can be achieved (Moody and Hernandez 1997). The adhesives are set through the use of a radio-frequency curing system (Moody and Hernandez 1997). It is important that the end pieces are free of knots to ensure sufficient joining strength (Moody and Hernandez 1997). Most commonly used are finger joints, which are used in the Nordic beams (Williston 1991). Other common options include butt joints and scarf joints (Williston 1991). The strongest joint type is the finger joint and it also maximizes the timber use (Williston 1991).

IMPORTANCE OF GLULAM

Historically, large dimensional lumber was not difficult to acquire but it has become increasingly hard to locate and harvest (Williston 1991). Glulam is a solution for specialty sized lumber. It has become difficult to acquire solid wood beams that have the same impressive dimensions that glulam beams can be created to have (Williston 1991).

Since wood is a carbon sink and wood products are mostly considered to be environmentally conscientious there has been an increase in the use of wooden products. This is done in an attempt to mitigate climate change (Ramage et al. 2017). Especially with responsible forestry practices, the impact of extracting the raw material is much less than steel or concrete (Hooper 2015).

Wooden structures can also be beneficial in areas prone to natural disasters, such as earthquakes (Ramage et al. 2017). Since the cellular structure of wood permits the material to flex, wooden structures have been proven to be more durable under earthquake conditions (Ramage et al. 2017). For example, in the Christchurch, New Zealand earthquake of 2011, the buildings that survived were the wood structures while almost all concrete structures had to be demolished (Wilkinson et. al. 2011). Another disaster situation that wood is superior in are fire situations (Williston 1991). Glulam specifically performs better than unprotected steel because of their larger diameter (Moody and Hernandez 1997). The diameter permits a slower reaction to the fire, only charring the surface initially (Moody and Hernandez 1997). Steel begins to soften and loose structural integrity at about 500ºF compared to glulam products, which can carry loads longer and at hotter temperatures (Moody and Hernandez 1997). The glulam products can be treated for additional fire resistance in the adhesives and with clear surface coatings (Moody and Hernandez 1997).

The public mostly does not accept the optimal performance of wooden products. However, the public perception of wooden buildings is changing and the common low-rise structures are being challenged (Ramage et al. 2017). Michael Green was a leader in initiating people's perception to change (Hooper 2015). He led the team that pushed the limits of the building codes in BC to prove that wood products such as glulam can be an effective material for constructing buildings (Hooper 2015). Recently an 18 story wood building was completed at the University of British Columbia, showing the potential of wood in tall mass timber buildings (UBC 2016). January 2015, Ontario increased the allowable height of wooden buildings to be up to 6 stories tall (Harvey 2016). The first 6 story wood buildings, under the new building code, are being constructed throughout Ontario (Harvey 2016).

KNOWN STRUCTURAL PROPERTIES AND TESTS

Density is the property of wood that can identify the most properties of the wooden sample. It is important to record accurate densities throughout an experiment (Williston 1991). The water-displacement method of density is an effective and accurate method of measure wood density (Smith, 1954). Since wood has many pores the water can seep into them and take an accurate volume measure (Smith, 1954).

The modulus of elasticity (MOE) and Modulus of rupture (MOR) are structural and strength properties. There are two effective methods of testing for MOE and MOR values: destructive or non-destructive (Verkasalo and Leban 2003). The non-destructive method analyzes the similarities of the other wood properties to determine MOE and MOR (Verkasalo and Leban 2003). The destructive method uses lab equipment to break specific sized sample sticks to determine the MOE and MOR following international standards for the testing, for example ASTM or ISO standards.

The structural properties throughout the wood product are not always consistent (Issa and Kmeid 2002). The glulam beams can be designed to use the stronger and better quality wood in the locations of the beam that will endure the most stress (Issa and Kmeid 2002). The parts of the product that are not designed to bear a load would gain the strategic placement of lesser grade wooden pieces (Issa and Kmeid 2002). The area where lesser strength properties can be used are the neutral axis layer in the center of the beam, while the compression and tension layers require more strength and hence higher graded lumber. This method optimizes the use of available wood supply and results in strong, effective and economically effective products (Issa and Kmeid 2002).

GRADING

Glulam products are graded and stamped similar to solid wood products but assessed with different criteria. All glulam products are graded through two grading methods: visual grading and E-rating (Moody and Hernandez 1997). Visual grading, is done by analyzing the structural properties of the wood (Moody and Hernandez 1997). This includes visually analyzing and categorizing the structural imperfections (Moody and Hernandez 1997). These include knot size, slope of grain, wane and other strength-reducing characteristics (Moody and Hernandez 1997). The E-rating process involves first the non-destructive method for determining stiffness (Moody and Hernandez 1997). The pieces that pass are then visually tested to determine if they meet the maximum allowable edge knot size in inches (Moody and Hernandez 1997). The modulus of elasticity (E) and allowable edge knot values are combined and a grade is given (Moody and Hernandez 1997).

A significant marking that is given to glulam products is if it is for outdoor or indoor use (Williston 1991). This is because of the adhesive capabilities. PF resins are suitable to the outdoor conditions however any adhesive that is not weather resistant is not suitable for outdoor use. In this case, the risk of failure becomes greater when exposed to outdoor conditions (Williston 1991).

WOOD KNOTS

Knots are a main defect of structural lumber. Knots can cause up to 60% of downgrade in lumber mills (Duchesne et al. 2005). It can decrease the strength properties of the wood drastically (Jozsa and Middleton 1994). There are two types of knots, live knots and dead knots. The live knots can lead to seasoning checks but the dead knots are a more serious defect (Jozsa and Middleton 1994). Live knots and the wood fiber grew together and there is still some connection. Dead knots and the surrounding wood fibres are separated, which removes all structural integrity from that spot (Jozsa and Middleton 1994). Knots in lumber are quantified by size and frequency (Jozsa and Middleton 1994). In glulam there are many small knots due to the nature of the small diameter used by Nordic in their manufacturing.

PROJECT AND HYPOTHESIS

The project will consider the literature and test the density, MOE and MOR values of the pieces of a glulam beam.

The Null hypothesis (H_o) is that there is no significant difference of;

1. The wood density values between glulam bolts
2. The wood density values between orientation
3. The wood density values between the joint type.
4. The MOE values between glulam bolts
5. The MOE values between orientation
6. The MOE values between the joint type.
7. The MOR values between glulam bolts
8. The MOR values between orientation
9. The MOR values between the joint type

MATERIALS AND METHODS

The glulam bolt is referred to as the initial material that was used and further cut into the required samples. The glulam bolts used in this study were composed of parallel 1” by 2” black spruce laminated pieces. Nordic, a glulam manufacturer in Quebec had manufactured them. The ASTM D 3737–08 standard for testing glulam pieces was followed. This ensures that the results from this study can be compared to the published values.

Using a Wood-Mizer portable mill at the Lakehead University portable mill site, these bolts were cut in half lengthwise and each half labeled as either parallel or perpendicular (ie. how the glue lines were oriented in the glulam bolts). The halves were then cut lengthwise into boards and labeled corresponding to their bolt half to keep track of the orientation. Figure 1 depicts a bolt that has been cut into boards.

Figure 1. A glulam bolt that has been cut in half then the boards cut from the two different orientations, parallel and perpendicular.

At the Lakehead University Wood Science Testing Facility (LUWSTF), the boards were then cut into 2cm high by 2cm wide and 30cm long sample sticks using a band saw. There were 40 sample sticks with no glue line in the center (clear samples) and 40 sample sticks with a glue line in the center. A label was given to each sample stick. An example of a label is G1B2╨C3. The first section (G1) of the name reflects the glulam bolt the sample originated from. This sample would have come from glulam bolt 1. The second section (B2) of the name reflects the board the sample originated from. This sample would have come from board 2. The third part of the name (╨) reflects the orientation of how the boards were cut. ╨ shows that the sample was from the parallel half of the bolt where the glue lines were parallel to the long axis of the bolt. It is also referred to as par. The other symbol used to label orientation is ⊥, which represents the perpendicular half of the bolt where the glue lines were perpendicular to the long axis of the bolt. The perpendicular orientation is also referred to as perp. The fourth part of the name (C) reflects if the sample is clear or has adhesives. If the C is present it is a clear sample. If it is absent the sample has adhesives in the center. The last part of the name (3) is the unique sample number from the board.

DENSITY

The water displacement technique of measuring wood density was used to determine the density (relative gravity) of the glulam samples. Five samples were taken from each category of; parallel clear, parallel with adhesive, perpendicular clear and perpendicular with adhesive (n=20). From the sample sticks that were chosen for the density test (selected from the test sticks) a portion of the stick was measured using the LUWSTF density jig, then it was cut. The density testing occurred with the samples at about 12% moisture content, the condition it was at when taken out of the conditioning chamber (chamber set at 65% relative humidity and 20 degrees Celcius). The weight of each sample was measured to the fourth decimal. The volume was then attained through water displacement in a beaker that was sitting on a scale. All results were recorded in the Wood Science App. Figure 2 shows the scale for the mass and the beaker and scale combination used to attain the volume with the Wood Science App running on the computer behind.

Figure 2. Scale for measuring the mass of the density samples and the scale and beaker combination for measuring the volume of the density samples.

The samples were then placed in the oven at 70 degrees Celcius for 4 days so all moisture could be removed. Afterward the process was repeated. The oven-dry weight was measured and recorded. The volume of the oven-dry samples, were then measured through the water displacement method in a beaker on a scale. These values were all added to the Wood Science App where the relative density was calculated.

MOE AND MOR

Testing for MOE and MOR was completed in the LUWSTF. The sample sticks were placed on the three-point testing platform of the Tinius Olsen H10K-T Universal wood testing machine. The sample was ensured to be straight and centered on the tool with the orientation of the growth rings either cupping down or the glue line oriented in the parallel or perpendicular to the long axis of the bolt, if present. Figure 3 displays the positioning on the three-point platform. There is a constant pressure applied (8mm/minute) and localized to the center of the beam. A specified rate of pressure is applied to the stick until the point of failure. The Tinius Olsen Test Navigator Software records the process and stops recording, once failure occurs. The software records the MOE and MOR values.

Figure 3. A sample stick ready to be tested for MOE and MOR values.

STATISTICAL TEST

A two-way ANOVA was used to analyze the density, MOE and MOR values. This statistical test is a comparison of the means. It is not determined where the significant difference is in the data, just if one exists between the mean data being compared. The glulam bolts, orientation and joint type were all compared separately to determine where the significant differences are (Laerd Statistics 2013). A Shaprio-Wilk test was completed to prove the normality of the data sets (Glass et al. 1972). See Appendix A for the raw data from the density, MOE and MOR testing.

RESULTS

Three assumptions were made in a two-way ANOVA test. The density, MOE and MOR data set met them all. The assumptions of normality were proven by the Shapiro-Wilk test (Glass et al. 1972). The wood density data was used in the Shapiro-Wilk test of normality and the result was a p-value of 0.07163. The resulting p-value for the MOE data set was 0.7501 and the resulting p-value for the MOR data set was 0.2879. Since the density, MOE and MOR data set had a p-value greater than 0.05 it can be accepted that there is a normal distribution throughout the data.

The second assumption is that there is homogeneity of variance (Glass at al. 1972). Consistent testing methods were used throughout the sample and testing procedure to ensure the same level of variance between sample groups. The third assumption is the assumption of independence (Glass at al. 1972). All of the samples used in this study are independent from each other.

WOOD DENSITY

The graphs, descriptive statistics and a two-way ANOVA were completed for the orientation and joint type variables. The glulam bolts and boards were not included in this section since only 20 samples were used. The 20 samples included samples from the 6 bolts; G10, G9, G8, G7, G6 and G3. It also included the 5 boards; B1, B2, B3, B4 and B5.

The orientation and joint type bar graphs have error bars with a 95% confidence interval, figure 4 and figure 5 respectively display this. Table 1 shows that the clear samples had a higher mean density compared to the samples with the adhesives. The clear samples were 621.6 (kg/m^3) and the samples with adhesive were 573.3 (kg/m^3). The parallel samples have a higher mean wood density compared to the orientation. Table 2 shows that the parallel samples have a wood density of 633.1 (kg/m^3) and that the perpendicular oriented samples had a wood density of 561.9 (kg/m^3). The differences between parallel and perpendicular orientation was proven to be significant through the two-way ANOVA test. Table 3 shows the significance values. The orientation has a significance of 0.002 which is less than 0.05 which proves its significance. The differences between the joint types are shown in table 4 and had a significance value of 0.051. Since this value is greater than 0.05 the difference in density for the two joint types are not significant.

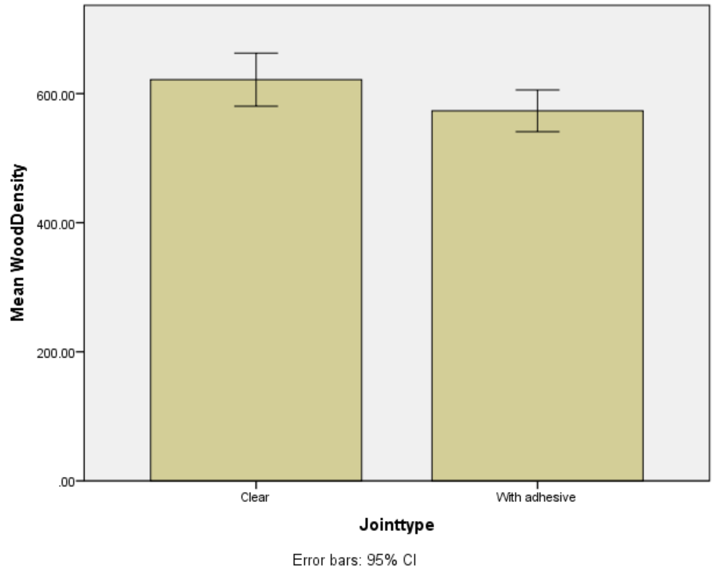

Figure 4. Comparison between the mean wood density for each joint type.

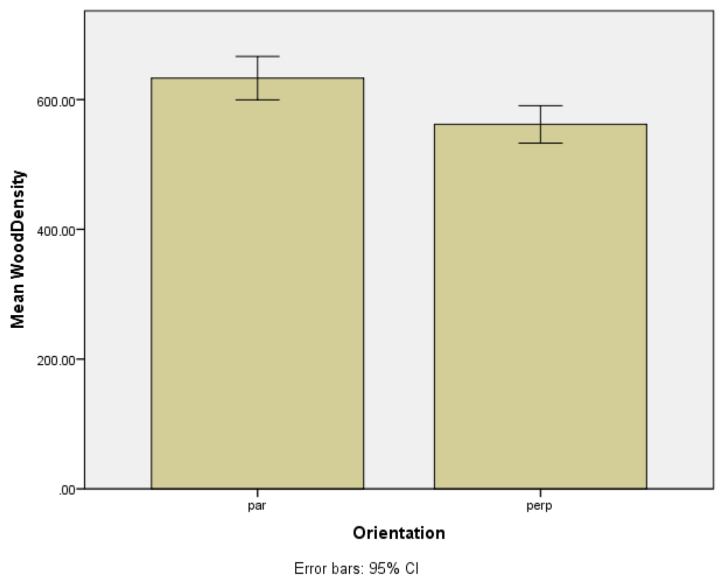

Figure 5. Comparison between the mean wood density for each orientation.

Table 1. Descriptive statistics for joint type wood densities (kg/m3).

Joint type	Mean(kg/m^3)	Std. Deviation	N
Clear	621.6064	57.34778	10
With adhesive	573.3341	45.18214	10
Total	597.4703	56.01824	20

Table 2. Descriptive statistics for orientation wood densities (kg/m3).

Orientation	Mean (kg/m^3)	Std. Deviation	N
par	633.0830	46.69986	10
perp	561.8575	40.31763	10
Total	597.4703	56.01824	20

Table 3. Significant differences of density values for orientation of the glue line.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	25365.337[a]	1	25365.337	13.328	.002
Intercept	7139414.228	1	7139414.228	3751.280	.000
Orientation	25365.337	1	25365.337	13.328	.002
Error	34257.492	18	1903.194		
Total	7199037.057	20			
Corrected Total	59622.829	19			

a. R Squared = .425 (Adjusted R Squared = .394)

Table 4. Significant differences of density for joint type.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	11651.091[a]	1	11651.091	4.372	.051
Intercept	7139414.228	1	7139414.228	2678.858	.000
Jointtype	11651.091	1	11651.091	4.372	.051
Error	47971.739	18	2665.097		
Total	7199037.057	20			
Corrected Total	59622.829	19			

a. R Squared = .195 (Adjusted R Squared = .151)

MODULUS OF ELASTICITY

The graphs, descriptive statistics and a two-way ANOVA were completed for all of the variables; glulam bolts, boards, orientation and joint type. The full set of 80 samples were used and included samples from the 6 bolts; G10, G9, G8, G7, G6 and G3. It also included the 5 boards; B1, B2, B3, B4 and B5.

The relationship between the means of the glulam bolts, orientation and the joint types were displayed graphically and are described in the following tables. A 95% confidence bar is applied to figure 6, figure 7, figure 8 and figure 9. Figure 6, figure 7 and figure 8 show the relatively consistent MOE values for the means of the glulam bolts, orientation and joint types respectively. Figure 9 displays the relationship of the mean MOE values for each of the orientations by joint type. This graph shows consistent values between the means.

Table 5 shows that G6 has the highest mean MOE value of 9928 MPa and G7 has the lowest value of 9139 MPa. Table 8 shows that the differences between the glulam bolts are not significant. The significance value is 0.378 which is greater than 0.05 therefore not significant.

Table 6 shows that the parallel orientation has a mean of 9431 MPa and the perpendicular orientation's mean MOE value is 9157 MPa. The parallel orientation is larger however, table 9 shows a significance value of 0.378. Since the significance is greater than 0.05. The difference between the mean MOE values for the orientations are not statistically significant.

The mean MOE values between joint types are in table 7. This table shows that the clear samples had the higher mean MOE value. However, table 10 shows a significance value of 0.312 for the mean MOE values of the two joint types. Since this value is higher than 0.05 there is no significant difference between the joint types.

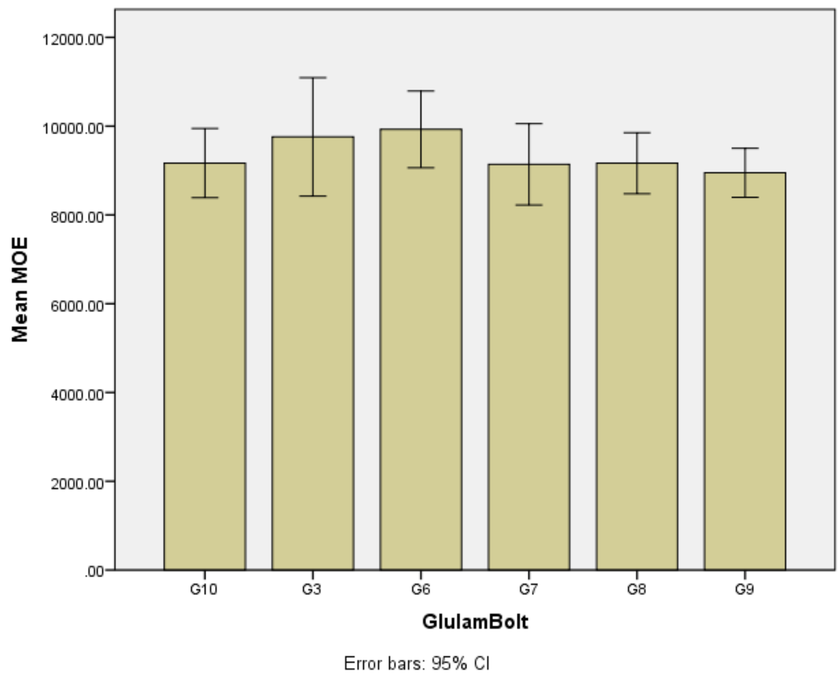

Figure 6. Comparison between the mean MOE (MPa) for each of the glulam bolts.

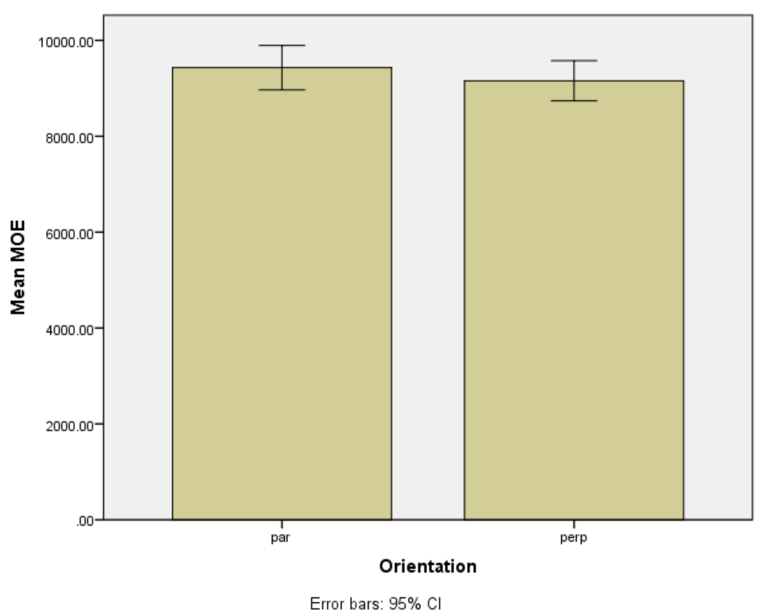

Figure 7. Comparison between the mean MOE (MPa) for each of the orientations.

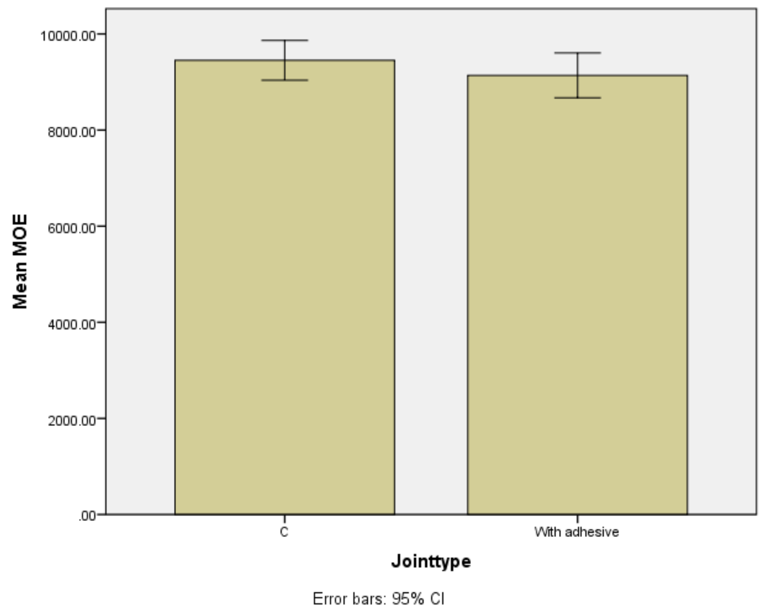

Figure 8. Comparison between the mean MOE (MPa) for each of the joint types.

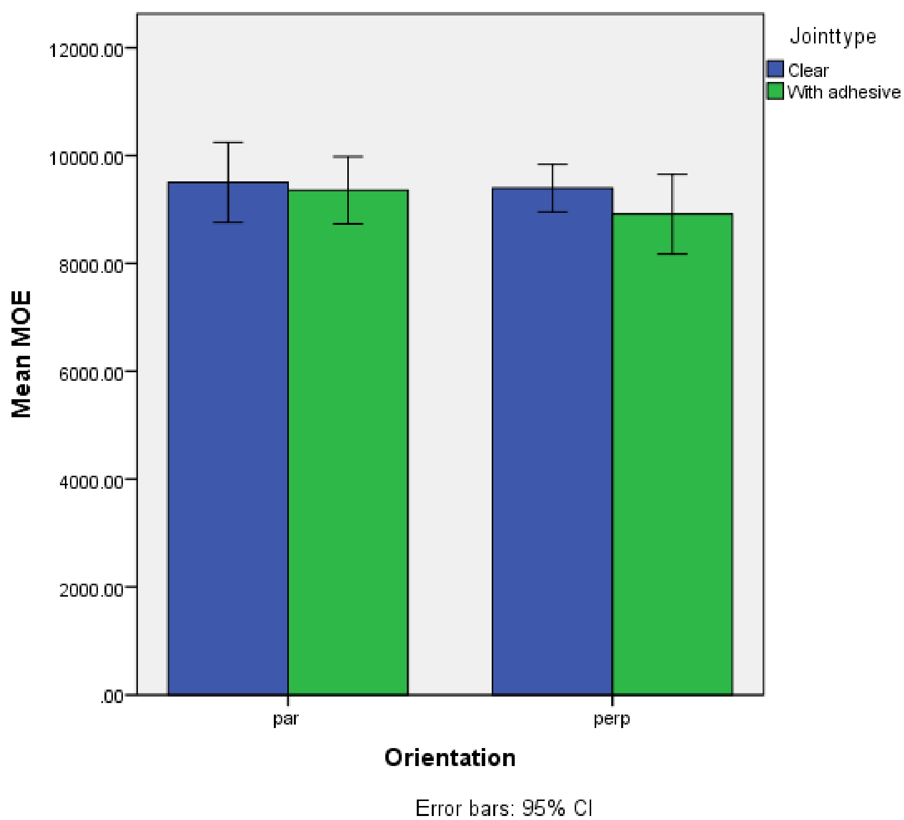

Figure 9. Comparison of the mean MOE (MPa) for each of the orientations by joint type.

DESCRIPTIVE STATS

Table 5. Descriptive statistics of MOE values for the glulam bolts.

Glulam Bolt	Mean (MPa)	Std. Deviation	N
G10	9168.0000	1091.81602	10
G3	9757.5000	837.31217	4
G6	9927.5000	1620.15431	16
G7	9139.3333	1654.99446	15
G8	9164.7059	1335.41715	17
G9	8949.4444	1109.51750	18
Total	9294.1250	1379.00872	80

Table 6. Descriptive statistics of MOE values for the orientations.

Orientation	Mean (MPa)	Std. Deviation	N
par	9431.0000	1449.86259	40
perp	9157.2500	1308.26561	40
Total	9294.1250	1379.00872	80

Table 7. Descriptive statistics of MOE values for the joint type.

Joint Type	Mean (MPa)	Std. Deviation	N
Clear	9451.0000	1291.88751	40
With adhesive	9137.2500	1460.35469	40
Total	9294.1250	1379.00872	80

MOE SIGNIFICANCE

Table 8. Significant differences of MOE values for the glulam bolts.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	10219192.440[a]	5	2043838.489	1.080	.378
Intercept	5303613917.000	1	5303613917.000	2803.092	.000
GlulamBolt	10219192.440	5	2043838.489	1.080	.378
Error	140012346.300	74	1892058.734		
Total	7060692300.000	80			
Corrected Total	150231538.700	79			

a. R Squared = .068 (Adjusted R Squared = .005)

Table 9. Significant differences of MOE values for the orientation.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1498781.250[a]	1	1498781.250	.786	.378
Intercept	6910460761.000	1	6910460761.000	3624.057	.000
Orientation	1498781.250	1	1498781.250	.786	.378
Error	148732757.500	78	1906830.224		
Total	7060692300.000	80			
Corrected Total	150231538.700	79			

a. R Squared = .010 (Adjusted R Squared = -.003)

Table 10. Significant differences of MOE values for the joint type.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1968781.250[a]	1	1968781.250	1.036	.312
Intercept	6910460761.000	1	6910460761.000	3635.545	.000
Jointtype	1968781.250	1	1968781.250	1.036	.312
Error	148262757.500	78	1900804.583		
Total	7060692300.000	80			
Corrected Total	150231538.700	79			

a. R Squared = .013 (Adjusted R Squared = .000)

MODULUS OF RUPTURE

The graphs, descriptive statistics and a two-way ANOVA were completed for all of the variables; glulam bolts, boards, orientation and joint type. The full set of 80 samples were used and included samples from the 6 bolts; G10, G9, G8, G7, G6 and G3. It also included the 5 boards; B1, B2, B3, B4 and B5.

Figure 10, figure 11, figure 12 and figure 13 have 95% confidence interval bars. Figure 10, figure 11 and figure 12 each show a comparison of the mean values for the glulam bolt, orientation, and joint type respectively. Figure 13 shows a comparison of the mean MOR values for each of the orientations by joint type. There appears to be similar mean values in each figure; 10-13.

Table 11 shows that the glulam bolt with the highest mean MOR value of 83.6 MPa is G6. The glulam bolt with the lowest mean MOR value of 77.2 is G7. The difference between the glulam bolts however, are not statistically significant. Table 14 shows the glulam bolts having a significance value of 0.473. Since it is greater than 0.05 it is not a significant difference.

The mean MOR orientation values are greater for the parallel samples at 82.1 MPa compared to the parallel samples having a mean MOR value of 78.8 MPa. This is shown in table 12. There is no significant difference between orientation. This is proven in table 15. The significance value is 0.204 which is greater than 0.05 and therefore not significant.

Table 13 shows the clear samples had a greater mean MOR value of 82.3MPa compared to the samples with adhesive with a mean MOR value of 78.6 MPa. Table 16 shows that although there is a difference between the joint type categories it is not statistically significant. The significance value is 0.157. Since the significance value is smaller than 0.05 it is not statistically significant.

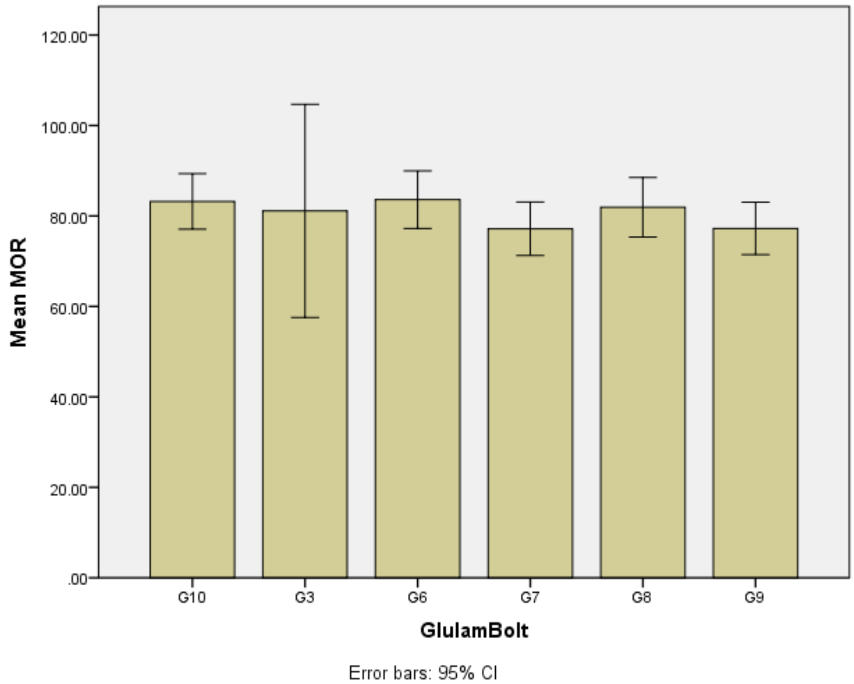

Figure 10. Comparison between the mean MOR (MPa) for each glulam bolt.

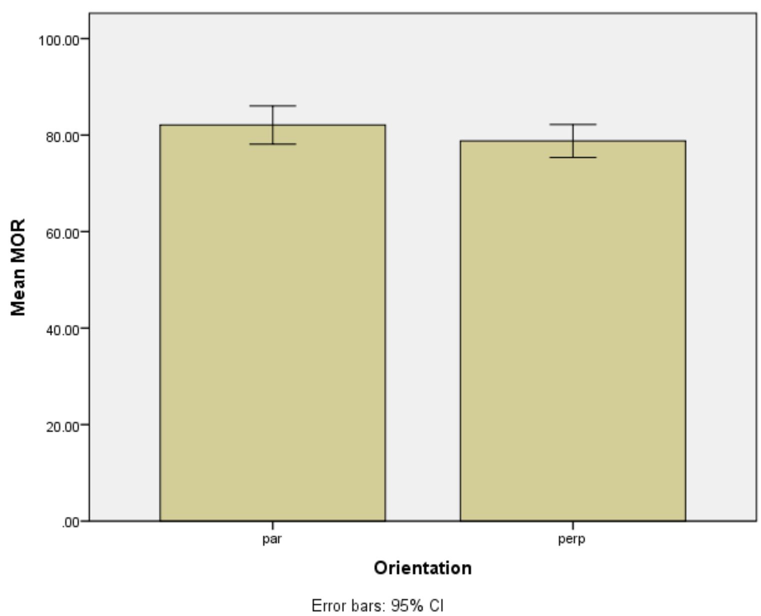

Figure 11. Comparison between the mean MOR (MPa) for each orientation.

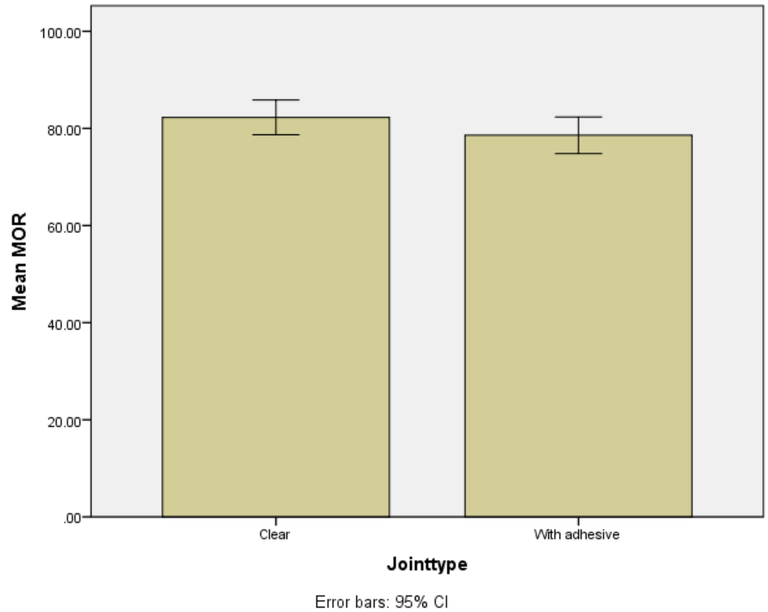

Figure 12. Comparison between the mean MOR (MPa) for each joint type.

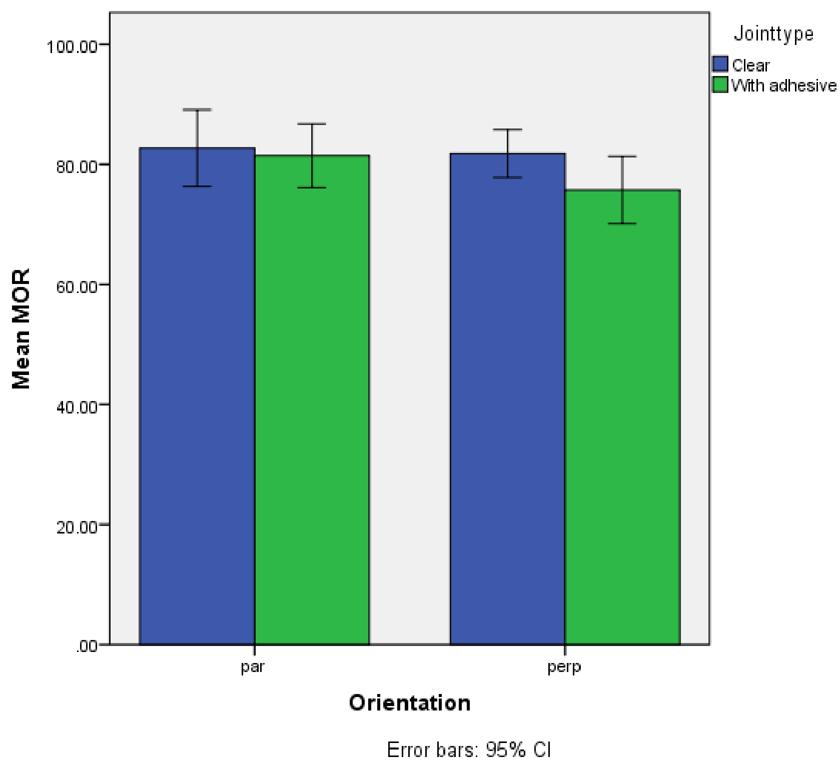

Figure 13. Comparison of the mean MOR (MPa) for each of the orientations by joint type.

DESCRIPTIVE STATS

Table 11. Descriptive statistics of MOR values for the glulam bolt.

GlulamBolt	Mean (MPa)	Std. Deviation	N
G10	83.2100	8.59566	10
G3	81.1000	14.80585	4
G6	83.6000	11.98199	16
G7	77.1667	10.66715	15
G8	81.9294	12.82511	17
G9	77.2278	11.65655	18
Total	80.4313	11.60160	80

Table 12. Descriptive statistics of MOR values for the orientation.

Orientation	Mean (MPa)	Std. Deviation	N
par	82.0850	12.35541	40
perp	78.7775	10.69482	40
Total	80.4313	11.60160	80

Table 13. Descriptive statistics of MOR values for the joint type.

Joint type	Mean (MPa)	Std. Deviation	N
Clear	82.2725	11.22474	40
With adhesive	78.5900	11.81932	40
Total	80.4313	11.60160	80

MOR SIGNIFICANCE

Table 14. Significant differences of MOR for the glulam bolts.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	622.398[a]	5	124.480	.920	.473
Intercept	395053.670	1	395053.670	2920.251	.000
GlulamBolt	622.398	5	124.480	.920	.473
Error	10010.774	74	135.281		
Total	528168.050	80			
Corrected Total	10633.172	79			

a. R Squared = .059 (Adjusted R Squared = -.005)

Table 15. Significant differences of MOR for the orientation.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	218.791[a]	1	218.791	1.639	.204
Intercept	517534.878	1	517534.878	3876.152	.000
Orientation	218.791	1	218.791	1.639	.204
Error	10414.381	78	133.518		
Total	528168.050	80			
Corrected Total	10633.172	79			

a. R Squared = .021 (Adjusted R Squared = .008)

Table 16. Significant differences of MOR for the joint type.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	271.216[a]	1	271.216	2.042	.157
Intercept	517534.878	1	517534.878	3895.763	.000
Jointtype	271.216	1	271.216	2.042	.157
Error	10361.956	78	132.846		
Total	528168.050	80			
Corrected Total	10633.172	79			

a. R Squared = .026 (Adjusted R Squared = .013)

DISCUSSION

Most of the variables tested with a two-way ANOVA were proven to have no significant difference. Every null hypothesis can be accepted except for number two. It is rejected as there is no significant difference for the wood density samples between the orientations, parallel and perpendicular. The parallel wood samples had a higher density.

The density results were the only results with proven significance. Since there was a smaller sample size it could be argued that these results are not statistically sound (Raudys and Jain 1991). There is an increase in error rate with a small sample set and any outliers in the data will skew the results more than outliers in a large sample set. There were no outliers in the density data set. Additionally, a larger sample size would have been more statistically accurate to compare the glulam bolts. There was an inconsistent number of samples representing the different bolts. This leads to inaccurate conclusions being drawn especially in a smaller sample size (Raudys and Jain 1991). Additionally, since glulam is composed of lumber that is taken throughout the length of the tree there is increased variability. The densest pieces will originate from the base of the tree and decrease in density as they approach the top (Duchesne et al. 2005). This additional variability supports the need for an increase in sample size (Raudys and Jain 1991).

The MOE and MOR values did not show a significant difference, however the clear samples had stronger MOE and MOR values. The higher values in the clear samples can be explained due to the inherently variable sample qualities (Issa and Kmeid 2002). There were samples with many small knots and samples with fewer knots.

Since knots are the main defect in wood products it is logical that there would be an effect on the results due to them (Duchesne et al. 2005).

The lack of significant differences could also be explained through the reproductive methods of black spruce. The sample beams are from Nordic, a manufacturer in Quebec that uses predominantly black spruce in their glulam beams (Nordic 2017). It is common in Quebec for black spruce trees to originate through seed (sexually) or through layering (asexually) (Torquato et al. 2013). This means the beams which included both spruce trees that were produced from seeds and also produced through layering (Torquato et al. 2013). The trees that originate through layering have lower MOE and MOR values compared to the trees that originate from seed (Torquato et al. 2013). This variance could influence the data set, ultimately skewing the results to favour higher MOE and MOR values for the clear samples.

The published results of the MOE are 11425 MPa and the MOR published values is 82.2 MPa (Cai and Ross 2010). The MOE and MOR results of this study were 9343 MPa and 80.4 MPa respectively, as seen in table 17. Although there was no significance found in the areas tested with an ANOVA the data set is valid since it is close to the published values. The resulting values are lower than the published values. This could be explained because the published values are for the entire glulam beam opposed to the resulting values which are the mean of the clear samples and samples with adhesive (Cai and Ross 2010).

Table 17. Published MOE and MOR values compared to the resulting MOE and MOR values of glulam (Cai and Ross 2010).

	Published Values (MPa)	Resulting Values (MPa)
MOE	11425	9343
MOR	82.24	80.38

CONCLUSION

Further analysis could be done with this data set to determine if a significant difference is within a more specific relationship. These relationships are;

- clear parallel samples and the parallel samples with adhesive
- clear perpendicular samples and perpendicular samples with adhesive
- clear parallel samples and clear perpendicular samples
- perpendicular samples with adhesive and parallel samples with adhesive
- samples with the glue line offset so it is not located in the neutral axis portion of the sample to see if this affects the strength

A significant difference may be determined between the first four relationships above using the density, MOE and MOR data.

The clear samples compared to the samples with adhesives may not have proven to have a large difference between them, however it is known that glulam beams are mechanically improved (Lam 2001). The pieces of glulam are combined to alleviate the defects and to increase strength qualities (Opfer 1997). The wood defects are hidden within the glulam beam but when the individual pieces are tested the defects become prominent (Lam 2001). Nordic's glulam beams would have to be tested as a whole bolt to determine the true density, MOE and MOR values. As a whole product glulam is considered to be an improved and effective building material (Opfer 1997).

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APPENDIX

RAW DATA

Table 18. Density data used in statistical analysis.

Bolt	Board	Orientation	Wood_Type	WD	WD_OD	MC
G3	B4	par	C	674.05	595.81	12.39
G3	B4	par	C	641.18	566.75	12.69
G8	B4	par	C	732.58	647.55	11.56
G6	B5	par	C	644.45	569.65	11
G10	B4	par	C	652.5	576.76	12.85
G10	B1	perp	C	553.6	489.34	12.15
G8	B4	perp	C	581.87	514.33	11.42
G9	B4	perp	C	573.81	507.21	12.01
G6	B1	perp	C	559.92	494.93	12.31
G10	B4	perp	C	602.11	532.22	12.24
G9	B3	perp	G	497.01	439.32	10.89
G9	B4	perp	G	490.06	433.18	11.11
G8	B3	perp	G	563.74	498.3	12.06
G8	B2	perp	G	612.09	541.05	11.65
G9	B2	perp	G	584.37	516.54	11.66
G8	B5	par	G	600.86	531.12	11.42
G8	B2	par	G	579.79	512.49	11.47
G7	B5	par	G	583.86	516.09	11.59
G7	B5	par	G	601.25	531.46	11.3
G6	B5	par	G	620.31	548.31	10.8

Table 19. MOE and MOR data used in statistical analysis.

Sample No	Bolt	Board	Orientation	Wood Type	Thickness	Width	MOE	MOR
G6B5parC2	G6	B5	par	Clear	16.92	19.85	12680	104.9
G7B1par1	G7	B1	par	Glue	17.66	18.28	12320	78.6
G7B5parC2	G7	B5	par	Clear	16.29	20.17	12210	104.5
G6B5par2	G6	B5	par	Glue	18.66	18.23	12010	88
G6B2perp1	G6	B2	perp	Glue	18.77	18.91	11810	95.5
G6B2perp3	G6	B2	perp	Glue	18.17	19.05	11640	93
G8B4parC2	G8	B4	par	Clear	17.89	19.95	11600	90.2
G9B2perp1	G9	B2	perp	Glue	18.98	19.02	11250	90.3
G6B1perpC1	G6	B1	perp	Clear	19.84	19.99	10900	77.8
G8B8parC1	G8	B8	par	Glue	20.01	20.16	10720	88.5
G8B1perpC1	G8	B1	perp	Clear	18.59	20	10660	102.1
G9B1parC2	G9	B1	par	Glue	19.93	20.22	10640	94.9
G3B4parC4	G3	B4	par	Clear	19.28	18.99	10600	102
G8B1perpC2	G8	B1	perp	Clear	18.09	19.86	10580	90.3
G6B5parC1	G6	B5	par	Glue	20.13	19.98	10570	93.3
G8B4perpC2	G8	B4	perp	Clear	19.65	19.88	10550	83.4
G10B4perpC1	G10	B4	perp	Clear	19.79	19.89	10510	88.3
G10B2perp2	G10	B2	perp	Glue	19.85	19.15	10500	81.6

G6B2perpC1	G6	B2	perp	Clear	19.92	19.91	10490	75.7
G8B5par2	G8	B5	par	Glue	18.78	18.56	10420	97.4
G6B4par1	G6	B4	par	Glue	17.35	17.43	10360	75.8
G8B8parC2	G8	B8	par	Glue	19.99	20.18	10350	99
G3B4parC3	G3	B4	par	Clear	17.79	17.64	10310	72.2
G10B2perpC2	G10	B2	perp	Clear	20.04	20.08	10170	94.3
G7B1perp2	G7	B1	perp	Glue	17.87	17.5	10130	85.3
G9B2par1a	G9	B2	par	Glue	19.36	20.1	9970	86.4
G7B5par1	G7	B5	par	Glue	19.4	18.49	9910	85
G9B5parC1	G9	B5	par	Clear	20.09	20.15	9860	87.6
G9B4parC2	G9	B4	par	Clear	17.05	20.01	9770	87.1
G10B2perpC1	G10	B2	perp	Clear	19.93	19.89	9650	87.3
G7B1perp1	G7	B1	perp	Glue	19.88	18.8	9640	64.1
G7B4parC2	G7	B4	par	Glue	20.33	20.24	9550	76.7
G6B3par2a	G6	B3	par	Glue	20.19	20.11	9510	90.8
G9B5par1	G9	B5	par	Glue	19.96	16.56	9440	83.2
G9B1par2	G9	B1	par	Glue	18.86	18.25	9390	83.6
G8B4par1	G8	B4	par	Glue	19.83	20.02	9390	73.6
G10B4perpC2	G10	B4	perp	Clear	20.2	20	9310	86.9
G3B4parC2	G3	B4	par	Clear	17.89	17.95	9300	69.2

G8B4par2	G8	B4	par	Glue	21.19	17.52	9240	87.2
G10B4perp3	G10	B4	perp	Glue	19.32	18.83	9190	88.7
G9B4perpC1	G9	B4	perp	Clear	18.88	19.9	9080	79.5
G6B1perp1	G6	B1	perp	Glue	19.91	18.93	8990	79.9
G7B2perpC1	G7	B2	perp	Clear	20.03	19.74	8990	74.9
G9B3perp4	G9	B3	perp	Glue	21.46	19.15	8960	84.5
G9B3perp2	G9	B3	perp	Glue	18.81	18.61	8920	73.9
G6B2par2a	G6	B2	par	Glue	19.82	19.97	8880	88.4
G8B4perpC1	G8	B4	perp	Clear	20.01	20.24	8880	85.9
G8B2perp1	G8	B2	perp	Glue	21.26	19.04	8870	84.9
G6B3perpC2	G6	B3	perp	Clear	19.94	19.06	8870	75.6
G6B4perp3	G6	B4	perp	Glue	17.19	19.11	8860	72.3
G7B5par2	G7	B5	par	Glue	19.42	18.56	8860	84.2
G3B4parC1	G3	B4	par	Clear	17.63	18.1	8820	81
G7B4perpC1	G7	B4	perp	Clear	20.13	20.28	8640	71.9
G9B4perpC3	G9	B4	perp	Clear	19.67	19.99	8640	78.1
G10B1perpC1	G10	B1	perp	Clear	19.75	20.04	8630	82.2
G7B1perp3	G7	B1	perp	Glue	17.23	19.31	8570	75.7
G10B3perpC2	G10	B3	perp	Clear	20.14	20.11	8570	85.8
G9B1par2	G9	B1	par	Glue	20.26	18.4	8560	77

G9B2perpC3	G9	B2	perp	Clear	20.01	19.92	8540	79
G8B5par1	G8	B5	par	Glue	18.35	18	8460	50.2
G7B3perpC1	G7	B3	perp	Clear	19.42	18	8420	66.4
G8B2par2a	G8	B2	par	Glue	19.43	19.89	8400	82.6
G7B1parC1	G7	B1	par	Glue	20.01	20.06	8390	81.1
G8B5parC1	G8	B5	par	Glue	19.97	20.03	8330	71.4
G7B1par2a	G7	B1	par	Glue	19.98	20.13	8220	79.4
G6B1parC2	G6	B1	par	Glue	20.43	20.28	8200	97.5
G9B1par1	G9	B1	par	Glue	17.87	18.94	8120	58.9
G6B4parC2	G6	B4	par	Clear	19.35	19.95	7910	64.2
G10B3perpC1	G10	B3	perp	Clear	19.44	17.67	7870	71
G8B4par1	G8	B4	par	Glue	22.1	18.35	7850	76.9
G8B3perp2	G8	B3	perp	Glue	20.23	19.22	7820	69.2
G10B4perp2	G10	B4	perp	Glue	19.3	19.72	7770	66.4
G8B5parC2	G8	B5	par	Glue	20.3	20.1	7520	72.2
G9B1perp2	G9	B1	perp	Glue	19.37	19.15	7510	64.6
G7B2perp1	G7	B2	perp	Glue	20.41	18.85	7490	68.1
G9B3perp1	G9	B3	perp	Glue	19.4	18.67	7360	56.8
G9B4perp1	G9	B4	perp	Glue	19.72	19.42	7310	58.3
G10B4parC1	G10	B4	par	Clear	17.94	20.01	7280	66

G6B1parC1	G6	B1	par	Glue	20.11	20.18	7160	64.9
G8B2par1a	G8	B2	par	Glue	19.96	19.98	6880	76.3
G7B4perp3	G7	B4	perp	Glue	19.42	18.95	5750	61.6